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MEchanical X-RAY (MEXRAY) Generator for Megavolt Radiography

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***Abstract*—Radiography is an important tool for determining the internal structure of objects of interest to the emergency response community. The inherent density of these objects often requires high-energy x-ray or gamma-rays which limits the range of available radiation sources/generators. Man-portable, low-power, megavolt sources currently do not exist. A megavolt x-ray system (MEXRAY) has been developed which uses mechanical charge-separation to create high-energy electrons which can then be used to create bremsstrahlung radiation. This approach relies on established physical principles e.g. charge separation, and the photoelectric effect, combined in a unique manner to produce a highly-efficient, low cost, compact, light-weight, high energy x-ray generator. This source can be used in either a pulsed or steady state manner making it suitable for multiple-pulse flash radiography, field radiography, or simply as a compact, low-impedance, high-energy electron injector.**

I. Introduction

Since the terrorist attacks of 9-11 the needs of the EOD community continue to evolve and the desire for higher-energy operation and even more compact pulsed-power radiation generating units has arisen [1]. Simply stated, the need to radiograph ever-smaller objects through ever-thicker shielded containers is a challenging problem. To resolve small features in a thick object, one needs to carefully match both the x-ray flux and the x-ray energy to obtain optimal statistical information [2]).

The weight of x-ray sources scales roughly like the cube of the endpoint energy. This powerful scaling holds true for all sources regardless of source type (e.g. radioisotope, accelerator, diode, or betatron), for a broad range of energies from 20 kVp to 20 MVp. Because of this strong scaling there are presently no lightweight sources that are commercially available between 400 kVp and 2 MVp, precisely the energy range necessary to penetrate thick, dense objects.

In addition, higher energy x-ray generators are large and expensive capital items which severely limits both their availability and applicability. These generators are normally insulated with oil meaning they are extremely heavy and have undesirable waste streams. Alternatively, high-energy radioisotope sources like Cobalt-60 have undesirable regulatory burdens associated with them.

A mechanical x-ray (MEXRAY) technology has been developed which uses mechanical work to raise the electrical potential of electrons stored on a capacitor by means of charge separation. Prior work on the concept of charge separation dates back to the 1700s. Volta's electrophorus [3] was used as a parlor trick to generate static-electric breakdown in air. The Wimshurst machine [4], [5], used a pair of counter-rotating wheels with capacitor plates mounted on them windmill-fashion to generate static discharge at voltages up to 100 kV. During the early development of the x-ray tube, it was common for Wimshurst machines to supply the high voltage to those tubes. However, as available technology improved, transformers rather than capacitors became dominant and remain so to this day.

In the 20th century, the most notable example of charge-separation was the Felici generator [6] which is essentially a Wimshurst machine operated in high-pressure hydrogen gas to improve the dielectric performance. Felici generators achieved operating voltages of approximately 250 kV with significant operating currents of several milliamps DC. Rotating machines are described by Isoya with operating voltages up to 1 MV [7], [8]. A summary of modern electrostatic accelerators is provided by [9].

Today, DC megavolt x-ray generators are rare. An example, shown in Fig.1, is a 1.4 MV, "capacitron" x-ray machine used by the National Bureau of Standards circa 1941 [10], [11]. Somewhat smaller, megavolt, vacuum Van de Graaff machines, developed by MIT [12] were also employed for radiation therapy in the post-world-war II era. Those machines could produce DC currents of approximately 1 mA, and radiation therapy doses of 50 R/min at 1 m at 1 MVp. These machines were often insulated with air or pressurized gas making them either very large, very heavy or both.

Adapting modern, vacuum-dielectrics to this situation, several prototype MEXRAY systems were built to operate at successively higher voltages with the goal of creating a man-portable 1 MeV system for thick-object radiography. The operation and the electro-mechanical theory developed to facilitate the design are described.

II. Design and Operation

The basic mechanism behind MEXRAY is the separation of parallel-plate capacitor plates in a vacuum. MEXRAY utilizes a small, high-voltage, DC-to-DC converter to charge the parallel plate capacitor with a voltage of up to 100 kV. The separation of the capacitor plates increases the voltage stored on the cathode capacitor plate in rough proportion to the separation distance. The high voltages are held across a small AK gap where electrons are liberated from the cathode

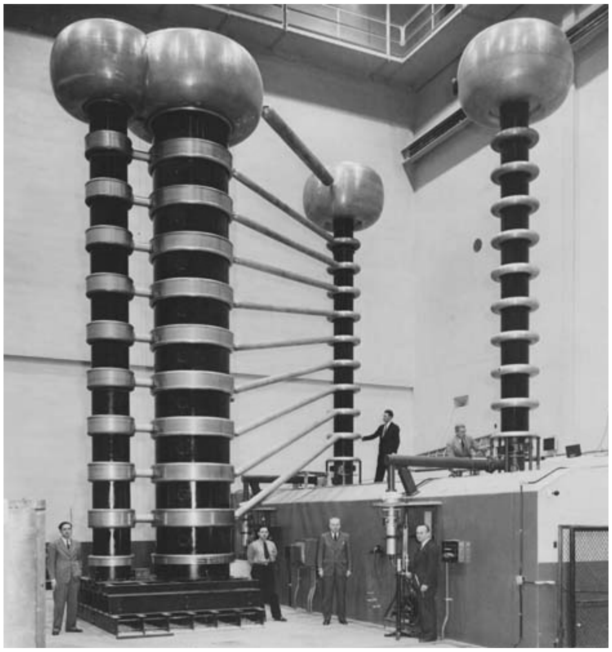


Fig. 1. Megavolt capacitron x-ray machine, circa 1941 [11].

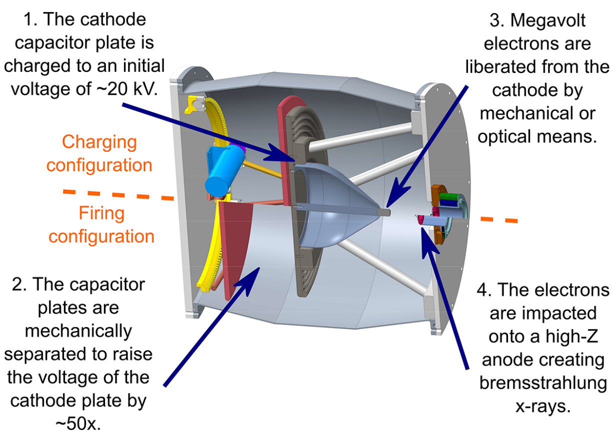


Fig. 2. Basic MEXRAY design

by field, or photo-emission and are accelerated onto a high-Z target. The impact creates bremsstrahlung x-rays with maximum energy equal to the separation voltage. The basic design principal of MEXRAY is shown in Fig.2 and the individual parts are described below.

A. Capacitor plates

The salient elements of MEXRAY are the two capacitor plates which are separated by a small vacuum gap (typically 500 μm). The cathode plate (Fig.3) is made from aluminum which is vacuum potted with two-part epoxy (equal parts Epon 815-C and Versamid-140) to minimize avalanche breakdown between the plates. To eliminate surface-tracking around the capacitor edges, a set of dielectric ears is machined into the back surface to snub the surface breakdown path which is inherently capacitively coupled.

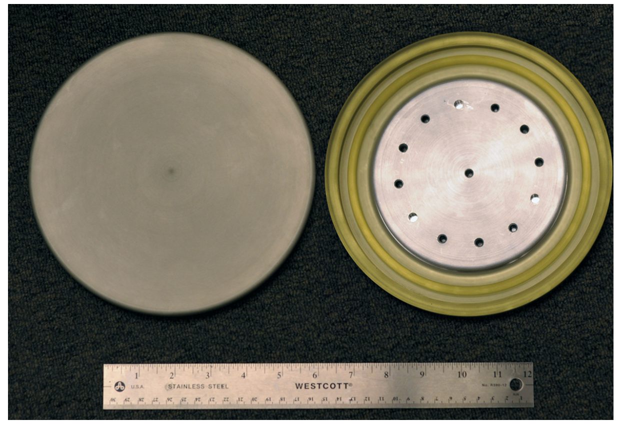


Fig. 3. Epoxy coated aluminum cathode capacitor plate front side (left) and back side (right).

Epoxy has a high outgassing rate which can lead to breakdown in the vacuum gap due to ion transport, we coated the epoxy with 75 μm-thick layer of Parylene C to passivate the outgassing surface. The anode plate (not shown) is the same size as the cathode plate but is made of a refractory metal or stainless steel polished to a 25 μm rms surface. Results with this combination demonstrate DC fields as high as 30 MV/m can be realized at 10^{-6} Torr vacuum before charge leakage and/or breakdown become significant problems.

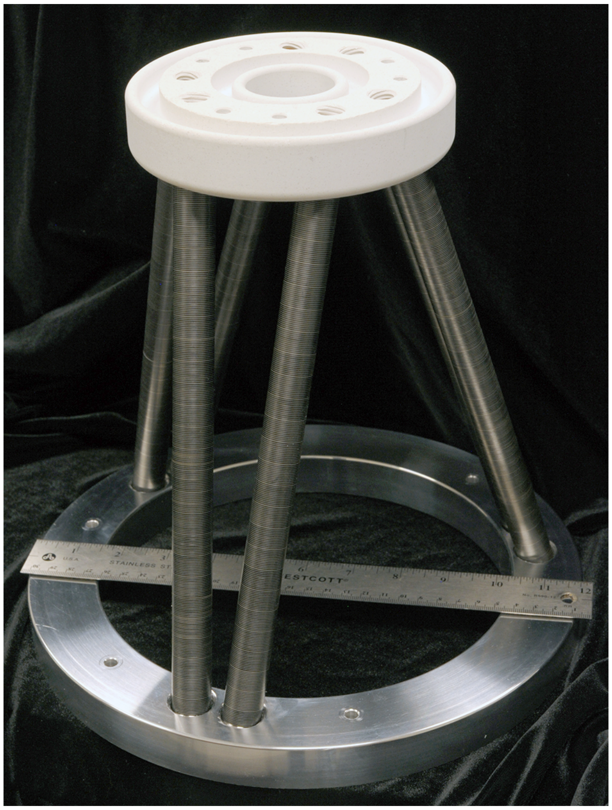
B. Charging mechanism

A mechanically/air actuated charging mechanism is used to charge the capacitor plates to an initial voltage of up to 20 kV. After charging the foot retreats to a low field part of the container to avoid breakdown to the charging foot. The charge is supplied from a high voltage power supply via a high voltage vacuum feedthrough.

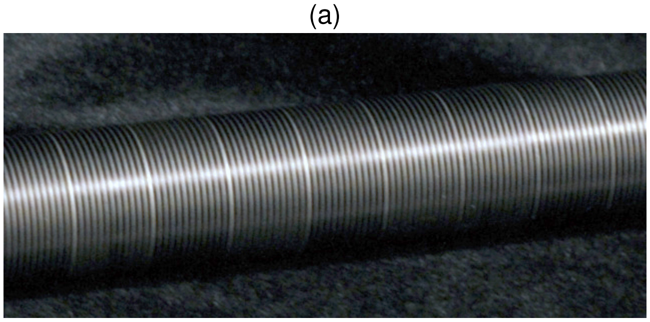
C. Hexapod insulator

A unique hexapod insulator is used to hold off the high voltage from the grounded outer vacuum vessel. The hexapod is essentially a truss that is wrapped around a cylinder so the insulating legs are acting purely in tension or compression. A hexapod structure was chosen due to its low weight, high strength, high stiffness and open structure for vacuum pumping. This configuration is an unusual insulator design; it is rare for insulators to only separate high voltages within a vacuum, instead insulators normally separate vacuum from another dielectric material like oil or water.

Various insulator materials were tested in a high voltage, DC test stand to determine their breakdown strength. To hold off 1 MV while retaining compact size requires DC breakdown field stress of 50 kV/cm. High Gradient Insulators (HGIs) which have been shown to offer an improvement in flashover performance by a factor of 2 to 5 when compared with conventional insulators [13]–[16]. However, HGIs suffer from poor tensile strength and high cost. The MEXRAY HGIs are part of the mechanical lifting mechanism and are required to have high tensile-strength. The necessary high tensile-strength



(a)



(b)

Fig. 4. (a) Hexapod insulator consisting of high strength high gradient insulator "legs", a mycalex attachment to the capacitor plate and an aluminum base to connect to MEXRAY. (b) Close-up view of high tensile strength HGI leg made from layered polyimide and stainless steel HGI donuts with an internal polyimide rod.

HGIs have been developed [17] which have greater than 100 kV/cm breakdown strength and greater than 600 psi tensile strength.

The insulating hexapod structure used in the 500kV MEXRAY system is shown in Fig.4. Care must be taken with the capacitor plate attachment as to minimize triple-point breakdown, particularly on the cathode surfaces. This consists of high strength HGI "legs" (Fig.4b), an aluminum base which attaches to the mechanical separation mechanism and a recessed Mycalex cathode shroud which connects to the cathode capacitor plate.

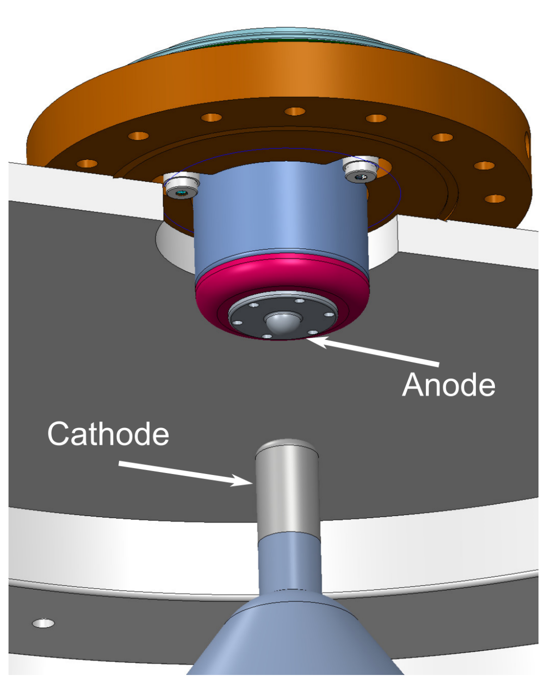


Fig. 5. AK gap showing cathode stalk, "hat anode" and initial UV LED source

D. Mechanical separation

Various methods exist to provide the necessary parallel actuator for plate separation. The initial separation has to be extremely parallel otherwise breakdown will occur between the plates. A unique, bellows mounted rotating hexapod design was chosen due to its light weight, extreme stiffness, and compact design. The motion is easily actuated with a simple vacuum feedthrough to a "drill motor". Limit switches on the upper surface limit the travel of the hexapod in both directions.

E. AK gap and cathode emission

The emission of bremsstrahlung x-rays is from the impact of electrons onto a high-Z target after the generation of electrons from the breakdown between an AK gap. A metal stalk is attached to the cathode capacitor plate with the required cathode at the tip. This stalk sits co-axially with an anode which makes up the AK gap (shown in Fig.5). Electrons which are created/generated in this AK gap are incident on a thin tungsten (transmission) target and bremsstrahlung x-rays are produced. The generation of electrons can be from field emission, emission via closing of the gap or photoemission.

For field emission the cathode consists of a high-beta material such as carbon velvet which spontaneously emits electrons when the field/voltage is sufficiently high to satisfy Fowler-Nordheim emission criterion [18]. It is well know that this type emission is hard to both predict and control.

The AK gap can also be mechanically shortened/decreased to increase the field and cause breakdown emission. This simple technique produces a reliable, and relatively prompt electron emission but suffers from a slightly increased x-ray spot size due to the "flying spot" nature of the anode.

Photocathodes have been demonstrated with MEXRAY to provide arbitrary control of the output dose rate. A photocathode is a negatively charged electrode which when struck by photons causes electron emission due to the photoelectric effect. Laser driven photocathodes have the advantage of prompt, intense emission, whereas LED driven photocathodes are used for steady-state, or slowly-modulated charge liberation.

Both laser and led driven photocathode emission has been demonstrated with MEXRAY using a bare magnesium photocathode. Using a Spectra-Physics Quanta Ray Indi quadrupled YAG UV laser (266 nm emission) multi-pulsing was demonstrated. The emission pulse width is approximately 15 ns (shown in Fig.6a). and the pulses are spaced 50 ms apart due to the 20 Hz operation of the laser.

Fig.6b shows the steady state emission using a UV LED light source which consists of eight 265 nm LEDS (Crystal-IS, KL-265-60R-SM-HC) focused onto the magnesium using 10 mm diameter ball lenses (Edmund optics #). Using the nominal 100 mA drive current per LED approximately 20 mW was imparted on the photocathode. Increasing the current to $\sim$200 mA delivered 35 mW. Based upon the low quantum efficiency observed (QE=5x10^{-7}) , we believe that a several-skin-depths-thick, oxide layer is forming on the magnesium.

F. Operation

The current MEXRAY system, shown in Fig.7a, weighs approximately 50 kg and has dimensions of 300 mm in diameter and 600 mm in height. The power is sourced from a drill battery (18 V, 15 A, 300 W) and is capable of maintaining vacuum using small, light-weight getters (Gamma Vacuum N100).

Operation with various cathode emission geometries has been demonstrated. Fig.7b shows an x-ray image obtained outside the vessel with 3 pulses of 500 kV x-rays using a UV laser driven magnesium photocathode (see section II-E).

The next generation MEXRAY system is currently under construction and will be capable of 1 MeV end-point operation. The outer dimensions are 60 cm diameter by 60 cm high and will weigh approximately 100 kg. Fig.8 shows the next generation design in charging and firing positions.

III. Theory and simulation/modelling

To study the parameter space of the voltage and electric field across the vacuum gap, MEXRAY can be modelled as a simple circuit as shown in Fig.9.

The two capacitors in series, a "dielectric capacitor" (epoxy), C_d, and a "vacuum capacitor", C_v, are described by,

$$C_d = \frac{\epsilon_0 \epsilon_r A}{d_d} \quad \text{and} \quad C_v = \frac{\epsilon_0 A}{d_v + \Delta d_v} \tag{1}$$

where ϵ_0 is the vacuum dielectric constant, ϵ_r the relative dielectric constant, A the area of the capacitor, d_d the dielectric thickness, d_v the initial vacuum gap and Δd_v the increase in vacuum gap.

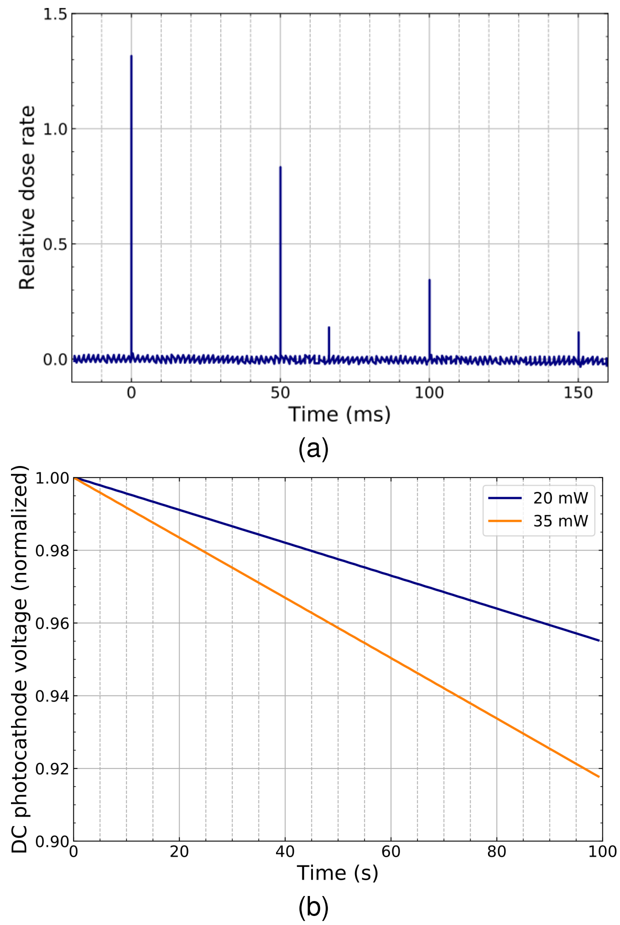


Fig. 6. (a) Magnesium photocathode demonstrating multiple pulsing using a UV laser and (b) magnesium photocathode under UV LED excitation showing steady state electron emission.

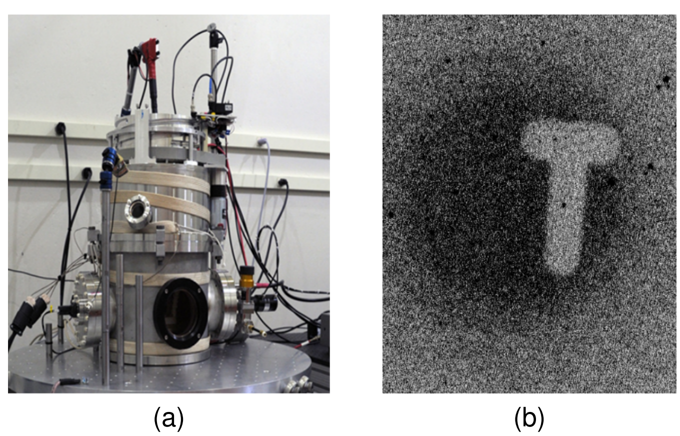


Fig. 7. Current operational MEXRAY system which operates at 500 kV with an input charge of 12 kV, and (b) x-ray image of a lead "T" obtained outside the vessel using a commercial BaFBr:Eu^{2+} storage phosphor.

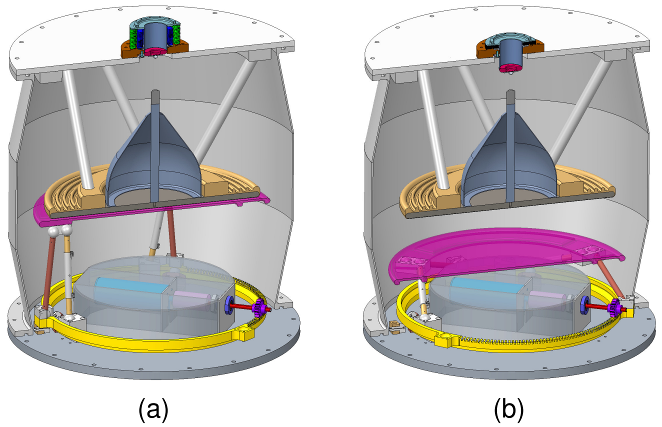


Fig. 8. Next generation design of 1 MeV operation MEXRAY system in (a) charging and (b) firing position.

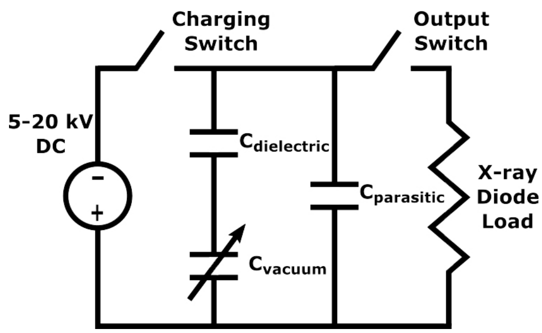


Fig. 9. MEXRAY circuit model.

It can be shown that the voltage, V_v, and the electric field, E_v, across the vacuum capacitor gap are described by,

$$V_v = \frac{V_c\left[C_p + \frac{\epsilon_0 \epsilon_r A}{d_d + d_v \epsilon_r}\right]}{\frac{\epsilon_0 A}{d_v + \Delta d_v} + C_p + \frac{d_d C_p}{\epsilon_r (d_v + \Delta d_v)}} \tag{2}$$

$$E_v = \frac{V_c\left[C_p + \frac{\epsilon_0 \epsilon_r A}{d_d + d_v \epsilon_r}\right]}{\epsilon_0 A + C_p\left(d_v + \Delta d_v + \frac{d_d}{\epsilon_r}\right)} \tag{3}$$

where V_c is the charging voltage and C_p is the parasitic capacitance.

To verify these simple model equations, the COMSOL Multiphysics code was used to compute voltage across the capacitor gap and experimental measurements of the capacitor voltage increase with increased vacuum gap were also made. Excellent agreement was found with the simple circuit model, COMSOL and experimental results, as shown in Fig.10.

COMSOL can be used to further study more complicated electrostatic problems used to guide design parameters of the MEXRAY system. As an example, a simple parametric study was performed on a hypothetical cylindrical vessel (fixed outer radius =1) and capacitor (radius = 0.4 - 0.9) with the goal of optimizing the vessel and capacitor size to obtain the maximum voltage multiplication. As the capacitor plate radius gets larger the voltage multiplication increases, shown

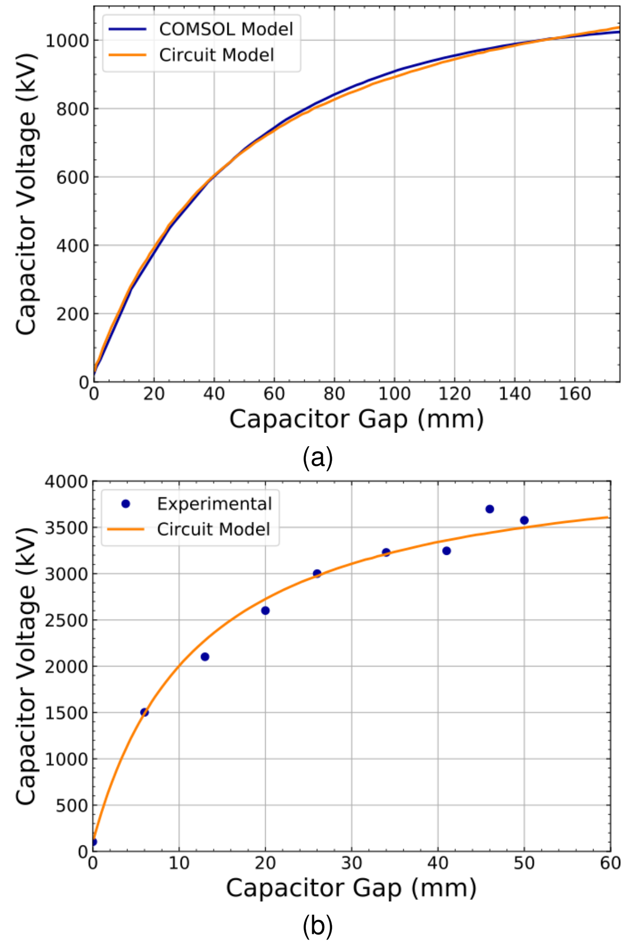


Fig. 10. AK gap voltage as a function of capacitor gap separation showing excellent agreement between (a) the circuit model and COMSOL and (b) the circuit model and experiment.

in Fig.11. This is a consequence of the parasitic capacitance of the vacuum vessel increasing (approximately linearly with size), while the parallel plate capacitance grows as the square of the radius. Therefore, the reduction in the net impact of parasitic capacitance, or higher voltage multiplication, favors a larger vacuum chamber in a roughly linear fashion.

The nature of megavolt x-ray generation gives rise to a roughly cubic scaling of dose with electron energy [19]. The compounding effect of size and energy gives rise to an extremely favorable scaling for MEXRAY systems above 500 kV the very regime MEXRAY intends to exploit.

From these types of parametric studies COMSOL was used to study electric potential, field-grading and parasitic capacitance for the next generation 1 MeV design. An example of the electric field and potential calculation for the next generation is shown in Fig.12, with the design having a 40 cm diameter capacitor plate in a 60 cm diameter vessel with 15 cm of plate separation.

IV. Summary

A 500 kV mechanical x-ray generator (MEXRAY) has been constructed. Enabling technologies such as high tensile strength HGIs and UV LED driven photocathodes allow for the construction of a compact, high energy x-ray generator capable of man portable radiography with 1 MeV end-point operation.

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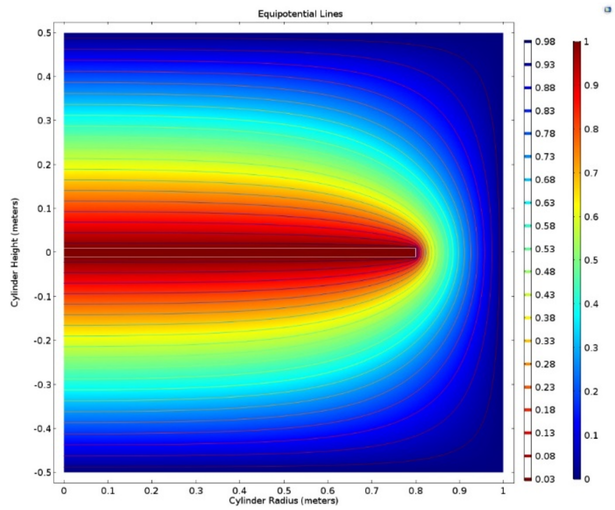
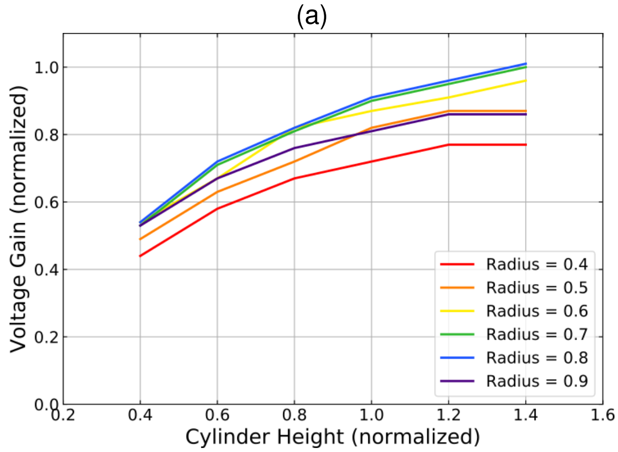


(a)



(b)

Fig. 11. (a) COMSOL electrostatic calculation of a hypothetical cylindrical vessel (fixed outer radius =1) and capacitor (radius = 0.4 - 0.9) and (b) voltage gain versus cylinder height (proportional to volume) for capacitor radius in the range 0.4 to 0.9.

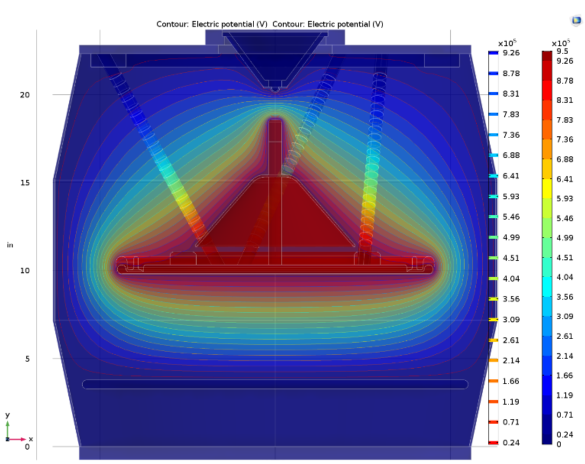


Fig. 12. COMSOL calculation of the electric potential of the next generation 1 MeV MEXRAY.

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